Mechanistic Investigation of Small-Scale Air-Sea Coupled Dynamics Using LES

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LONG-TERM GOAL

The long-term goal is to understand the detailed mechanisms of coupled boundary layers air-sea transfer (CBLAST) by performing DNS/LES of both air and ocean turbulent flows with coupled free-surface boundary conditions. The primary focus and an ultimate object is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean wave boundary layer (WBL).

OBJECTIVES

The scientific and technical objectives of this project are to:

- develop DNS/LES capabilities for the coupled air-ocean-wave flow field, with the focus on air and water turbulent motions under the influence of coupled free-surface boundary conditions

- elucidate the structures and dynamics for turbulent flows in the vicinity of the air-sea interface

- perform direct quantitative comparison and cross-validation of DNS/LES simulations with experimental/field measurements

- develop, calibrate and validate specialized physics-based subgrid-scale (SGS) models for the atmosphere-ocean WBL

- assess the physical mechanisms of the key WBL transport processes

- characterize and parameterize the momentum, mass and heat transfer process in WBL for coupled air-ocean-wave boundary modeling

APPROACH

We develop two complementary computational methods for the DNS and LES of coupled air and ocean turbulent flows: at low wind speed (<5 m/s), a boundary interface tracking method (BITM) which utilizes coupled free-surface boundary conditions based on boundary-fitted meshes; and at moderate wind speed (>5 m/s), where the waves steepen/break, an Eulerian interface capturing method

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14. ABSTRACT
The long-term goal is to understand the detailed mechanisms of coupled boundary layers air-sea transfer (CBLAST) by performing DNS/LES of both air and ocean turbulent flows with coupled free-surface boundary conditions. The primary focus and an ultimate object is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean wave boundary layer (WBL).

15. SUBJECT TERMS

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(EICM) based on a level set approach. These developments are at the cutting edge of computational free-surface hydrodynamics.

The BITM method solves the incompressible Navier-Stokes equations for both air and water. The transport of scalars is also implemented in the BITM. At the air-water interface, fully-nonlinear free-surface coupled boundary conditions are used, with the kinematic boundary condition requiring that the interface remains a material surface, and the dynamic boundary condition requiring a stress balance across the interface. The governing equations are discretized using a pseudo-spectral method in the horizontal directions and a finite-difference scheme in the vertical direction. Explicit Runge-Kutta schemes are used for the time integration of the flow field and the motion of the air-water interface.

In EICM, the air and water together are treated as a system with varying density, viscosity and diffusivity. A continuous scalar, a level set function, representing the signed distance from the interface is used to identify each fluid. The fluid motions are governed by the Navier-Stokes equations while the scalar is advected with the flow governed by a Lagrangian-invariant transport equation. The governing equations are discretized on an Eulerian grid using a finite-difference scheme.

WORK COMPLETED

For the fiscal year of 2002 which is the second year of this five-year project, our main focuses are: (i) further development of robust and efficient of DNS/LES computational tools for air-sea coupled flows; (ii) calibration and cross-validation with existing measurements; and (iii) investigation of turbulence-wave interaction mechanisms at small spatial scales with low to moderate wind speeds. Substantial progress has been made, which includes:

- Further development of high-performance DNS/LES capability for air-water-wave turbulent flows. The numerical methods of BITM and EICM developed in this project substantially improve the accuracy and physical meaning of the numerical results over existing computational approaches. The codes are optimized on high-performance parallel computing platforms to provide high-resolution, large-scale results in a timely manner.

- High-resolution simulation of coupled air-water flow during wave breaking. Our primary focuses in the fiscal year of 2002 were steep turbulent waves and unsteady spilling breaking waves. Extensive simulations have been performed and the obtained dataset provides a framework for the detailed analysis of air-water-wave interactions.

- Investigation of the detailed mechanism of wave-turbulence interactions. The evolution of coherent vortical structures in both air and water flows is elucidated. The correlation of vortical structures with turbulence transport and dissipation processes is identified and quantified.

- Obtaining a physical understanding of the energy transfer and dissipation process in water and air during wave spilling-breaking events. Based onsimulation results, we quantified the transfer process of turbulent kinetic energy across the air-sea interface and the respective dissipation rates in air and water. This understanding establishes a physical foundation for the development of improved, physics-based turbulence modeling of atmosphere-ocean wave boundary layer.

RESULTS

We have performed extensive simulations for air-sea coupled flows with the focus on turbulence-wave interactions and unsteady spilling breaking waves. From simulations, we obtain detailed description on the statistical, structural, and dynamic aspects of air-water-wave interactions. Our simulations have revealed some unique features of turbulent flows in the atmosphere-ocean wave boundary layer, which established a basis for the development of physics-based turbulence modeling.

Figures 1 to 3 show a typical example of unsteady wave breaking simulated with the EICM method developed in this project. Coupled air and water motions are computed with a plane progressive wave. The initial condition is an impulsively started, overly steep surface wave. The large amplitude of the wave leads to unsteady wave breaking. Detailed comparison has been performed against existing measurement data (*e.g.* Rapp & Melville 1990) and satisfactory agreement is obtained.

From simulations we have identified coherent vortical structures in the air and water near the breaking wave. In Figure 1 the contours of vorticity are plotted, with blue representing clockwise rotating vortices and red counter-clockwise rotating vortices. It is shown that strong vorticity appears near the wave face on the airside. Strong vortex pairs exist on the waterside. What is also of interest is the presence of vortex shedding behind the wave crest.

We found that the above coherent vortices are closely related to the dissipation of kinetic energy. Figure 2 plots the distribution of energy dissipation rate. Red color corresponds to high dissipation rate. Comparison with Figure 1 reveals the correlation between the dissipation process and vortex structures. Significant dissipation rate exists near the wave crest. In general, the dissipation rate in water is higher than that in air, because the density of water is 1000 times larger than that of air. Nevertheless, the dissipation in air is also noticeable near the wave face. The vortex shedding behind the wave crest also contributes to energy dissipation.

While Figures 1 and 2 show the spatial structure of the breaking wave at one time instance, Figure 3 shows the time evolution of energy dissipation during the entire wave-breaking event. The total dissipation rates in air and water are plotted as a function of time. Wave breaking occurs between $t\sim2$ and $t\sim10$. The unsteady nature of the dissipation process associated with the wave breaking is clearly shown. Figure 3 also shows that although the majority of dissipation comes from the waterside, the dissipation in the air cannot be neglected. Indeed, airside dissipation becomes significant in the middle of wave breaking. The physics revealed here is essential to the improvement of turbulence modeling.

IMPACT/APPLICATION

This project is an essential numerical part of an overall coordinated effort involving experimentalists, air-sea modelers, and physical oceanographers. Our numerical simulations will provide detailed descriptions of the air-sea-wave boundary layer at small scales, which are critical for the cross-validation with measurement, investigation on the transport process, and parameterization for the prediction of air-sea interaction.

TRANSITIONS

The extensive numerical datasets obtained from this project will be used for the cross-calibration with measurements. The numerical results will be used to provide information on physical quantities difficult to measure and to verify experimental databases. The numerical capabilities developed in this project will also provide a framework for the parameterization of coupled air-ocean-wave dynamics.

REFERENCES

Rapp R. J. & Melville W. K. 1990 Laboratory measurements of deep-water breaking waves. *Proc. R. Soc. Lond. A*. **331**(1622): 735.

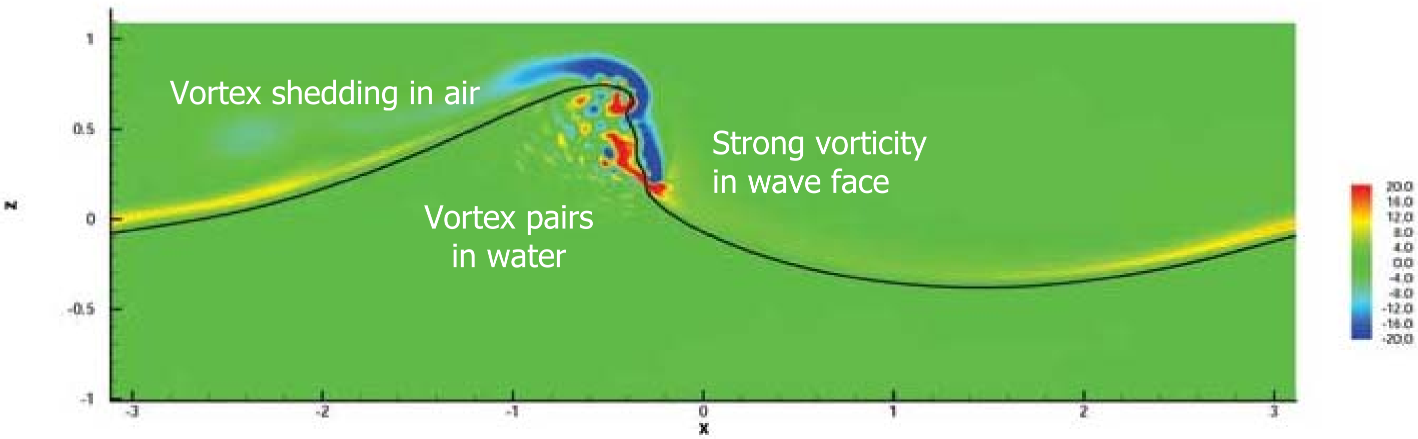

Figure 1. Vorticity distribution in air and water during wave-breaking event.

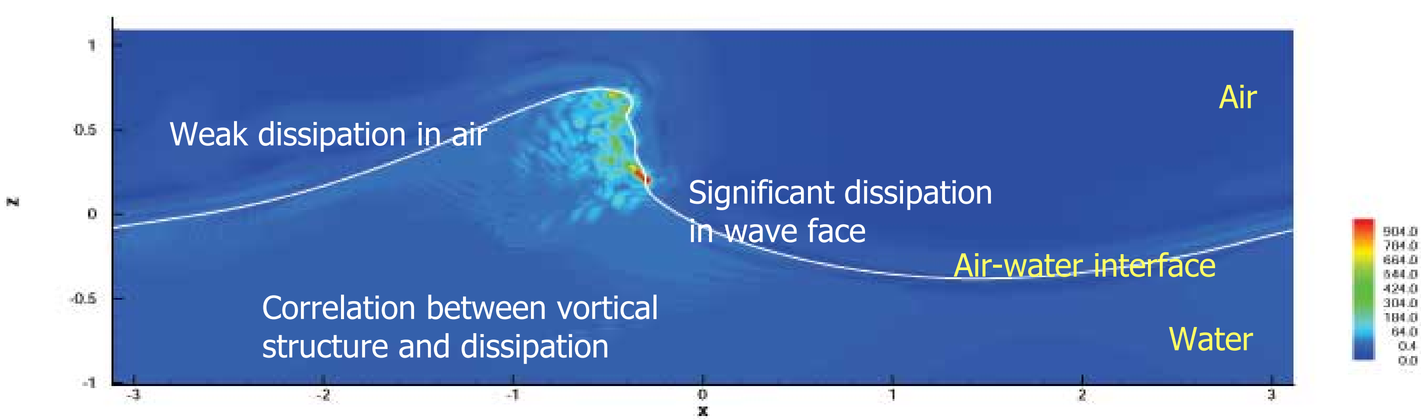

Figure 2. Distribution of energy dissipation rate in air and water during wave-breaking event.

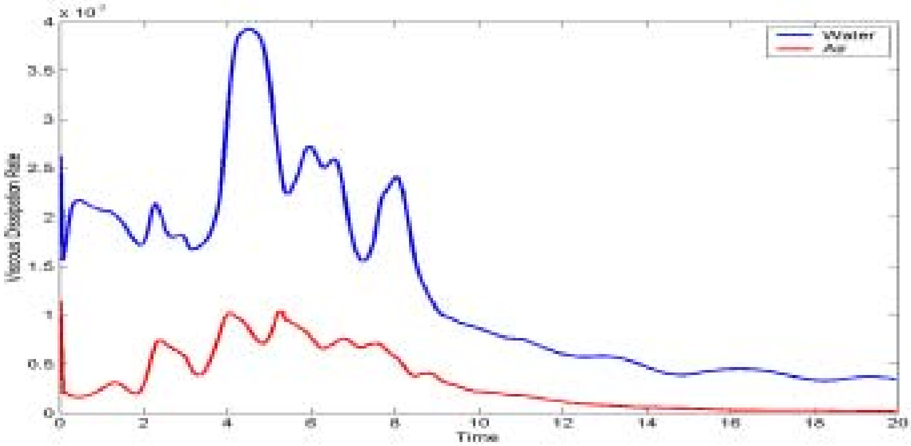

Figure 3. Time evolution of energy dissipation rate in air and water.